

Examination of uncertainties in nuclear data for cosmic ray physics with the AMS experiment

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(Dated: October 2015)

High-energy Li-Be-B nuclei in cosmic rays are being measured with unprecedented accuracy by the AMS experiment. These data bring valuable information to the cosmic ray propagation physics. In particular, combined measurements of B/C and Be/B ratios may allow to break the parameter degeneracy between the cosmic-ray diffusion coefficient and the size of the propagation region, which is crucial for dark matter searches. The parameter determination relies in the calculation of the Be and B production from collisions of heavier nuclei with the gas. Using the available cross-section data, I present for the first time an evaluation of the nuclear uncertainties and their impact in constraining the propagation models. I found that the AMS experiment can provide tight constraints on the transport parameters allowing to resolutely break the degeneracy, while nuclear uncertainties in the models are found to be a major limiting factor. Once these uncertainties are accounted, the degeneracy remains poorly resolved. In particular, the Be/B ratio at ~ 1 – 10 GeV/n is found not to bring valuable information for the parameter extraction. On the other hand, precise Be/B data at higher energy may be useful to test the nuclear physics inputs of the models.

PACS numbers: 98.70.Sa, 96.50.sb, 25.40.Sc, 95.35.+d

I. INTRODUCTION

Understanding the cosmic ray (CR) transport processes in the Galaxy is a major subject in modern astrophysics. The CR transport is studied using data on secondary nuclei (*e.g.*, Li-Be-B), which are created by fragmentation of heavier elements, and primary nuclei (*e.g.*, H, He, C-N-O), which are produced and accelerated in Galactic sources. Secondary-to-primary ratios, and in particular the B/C ratio, are used to constrain the Galactic diffusion coefficient, D , and the half vertical extent of the propagation region, L [1–3]. For a rigidity-dependent diffusion coefficient $D \approx D_0 \mathcal{R}^\delta$, the B/C ratio fixes both δ and the D_0/L ratio. The degeneracy between D_0 and L may be lifted using data with unstable isotopes, such as the $^{10}\text{Be}/^9\text{Be}$ isotopic ratio or the Be/B elemental ratio [4, 5]. Hence, combined measurements of B/C and Be/B ratios may provide the determination of the basic CR transport parameters. Understanding CR transport is crucial to reliably predict the secondary production of antimatter and to set stringent limits on dark matter annihilation signals. The parameter L is of great importance for assessing the dark matter signal.

The spectra of B and Be nuclei are now being measured by the Alpha Magnetic Spectrometer (AMS) experiment in the International Space Station (ISS). Recent measurements of CR protons [6] and preliminary results on light nuclei [7, 8] show that AMS is probing the GeV–TeV energy region to a $\sim \%$ level of accuracy. With this standard of precision, it is now timely to assess the theoretical uncertainties of the model predictions. In particular, calculations of Be-B production rates rely on several cross-section (XS) estimates. Propagation models make use of semi-empirical XS formulae calibrated to accelerator data. Thus, the accuracy of the inferred transport

parameters is directly linked to the quality of the available measurements on nuclear fragmentation.

The aim of this paper is to estimate the *nuclear uncertainties* in CR propagation and to investigate how they affect the determination of the CR transport parameters. In particular, I will focus on the anticipated AMS data on the B/C and Be/B ratios and their connection with the D_0/L degeneracy problem. For this purpose, I have gathered all available XS data for Be and B production from B-C-N-O collisions off hydrogen target. These data have been used to constrain the XS parameterizations in order to estimate their uncertainties. The resulting XS errors have been therefore converted into theoretical uncertainties for the model predictions and, finally, into uncertainties on the transport parameters that can potentially be inferred by AMS.

II. CALCULATIONS

The CR propagation model — This work relies on the diffusive-reacceleration model implemented under the code GALPROP, which numerically computes the equilibrium spectra of CR leptons and nuclei for given source functions and boundary conditions [9, 10]. I define a *reference model* as follows. The source spectra are taken as broken power-law functions, $q_j \propto (\mathcal{R}/\mathcal{R}_B)^{-\nu}$, with index $\nu_1 = 1.9$ ($\nu_2 = 2.38$) below (above) $\mathcal{R}_B = 9$ GV. The diffusion coefficient is taken as $D(\mathcal{R}) = \beta D_0 (\mathcal{R}/\mathcal{R}_0)^\delta$, with $D_0 = 5 \cdot 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $\delta = 0.38$, and $\mathcal{R}_0 = 4$ GV. The Alfvén speed is $v_A = 33 \text{ km s}^{-1}$. The cylindrical diffusion region has radius $r_{max} = 30 \text{ kpc}$ and half-height $L = 3.9 \text{ kpc}$. A large nuclear reaction chain is set up, describing the production of secondary j -type nuclei from fragmentation of heavier k -type nuclei. The fragmen-

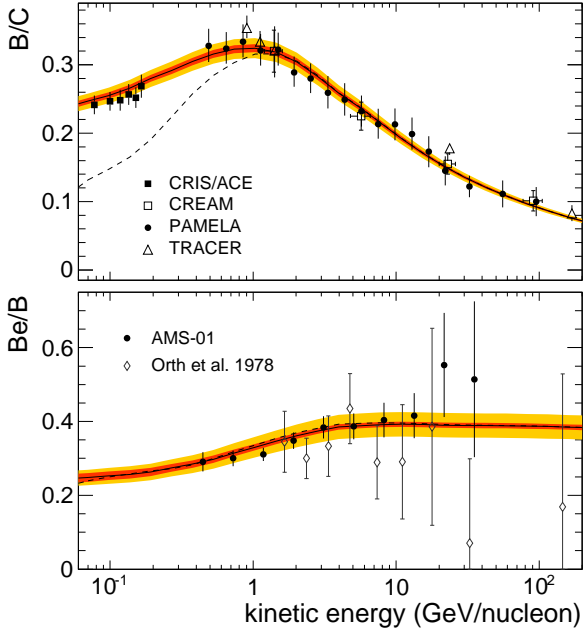


FIG. 1. (Color online) Elemental ratios B/C (top) and Be/B (bottom) from the reference model in comparison with the data [15–20]. The yellow bands are the estimated nuclear uncertainties (from Fig. 2). The red bands reflect the estimated parameter uncertainties for anticipated AMS data (from Fig. 3).

tation rate is $\Gamma_{k \rightarrow j} = \beta_k c n \sigma_{k \rightarrow j}^i(E)$, where n_i are the number densities of the ISM nuclei ($n_H \cong 0.9 \text{ cm}^{-3}$ and $n_{He} \cong 0.1 \text{ cm}^{-3}$) and $\sigma_{k \rightarrow j}^i$ is the production XS off i -type target at energy E . Under GALPROP, production XS's are evaluated from interpolation/fits to the data or from nuclear codes, such as CEM2k or LAQGS, eventually normalized to the data [11–14].

Nuclear uncertainties — Data on isotopically separated targets and fragments have been collected by several experiments, but only in narrow energy ranges. A compilation is shown in Fig. 2 for the production of ^{10}B , ^{11}B , ^7Be , ^9Be , and ^{10}Be isotopes from fragmentation of ^{12}C , $^{14,15}\text{N}$ and ^{16}O off hydrogen target at energy between 30 MeV/n and 10 GeV/n. For Be production, I have also considered *tertiary* reactions such as $\text{B} \rightarrow \text{Be}$, *i.e.*, those reactions where the progenitor nuclei are of secondary origin. All these processes account for $\gtrsim 90\%$ of the Be and B production. At energy above than a few GeV/n, all the XS's are nearly constant in energy. The data in Fig. 2 are compared with XS parameterizations from GALPROP and from the popular formulae WNEW [32–34] and YIELDX [35]. Following earlier studies [36, 37], the XS uncertainties are determined by a re-fit of the GALPROP parameterizations $\sigma_G(E)$ to the data. For each reaction, the corresponding XS are fit with the function $\sigma_H(E) = a \sigma_G(bE)$, where a and b are free parameters representing normalization and energy scale. This procedure allows to determine a new set of XS's and their associated uncertainties corresponding to

one-sigma confidence intervals. The uncertainty bands are shown in Fig. 2. The new XS's are often close to the original σ_G values, but the Be production in GALPROP is found to be over-estimated by a few percent. Such a Be overproduction was also reported in Aguilar et al. [15]. The estimated XS errors have been converted into uncertainties of the secondary/tertiary production terms and then propagated at Earth. Typical uncertainties are found to be $\sim 5\%$ for B production and $\sim 7\text{--}10\%$ for Be production, with $\sim 10\%$ for ^{10}Be productions. The corresponding uncertainties in the B/C and Be/B ratios are shown in Fig. 1 for the reference model (yellow bands).

Modeling the AMS performance — I consider the B/C ratio at 2 - 200 GeV/n and the Be/B ratio at 1 - 100 GeV/n. For these ratios, I compute the anticipated AMS data under the reference model. The number of j -type particles detected by AMS in each energy bin is estimated via the convolution of the CR flux with the detector acceptance [38], $\Delta N_j = \int \Phi_j \mathcal{G}_j \mathcal{T}_j dE$, where Φ_j is the input spectrum, \mathcal{G}_j is the total detector acceptance and \mathcal{T}_j is the effective exposure time for a total data taking period T_0 . All input spectra are solar-modulated under the force-field approximation [39], using $\phi \cong 550 \text{ MV}$ for the AMS observation period. I consider the case of 10 bins per decade, log-uniformly spaced in energy, and a total exposure of $\mathcal{G}T_0 \cong 100 \text{ m}^2 \text{ sr day}$. The effective exposure time must account for the geomagnetic field modulation which suppresses the Galactic CR flux below the cut-off rigidity, $\mathcal{R}_C \approx 0.5\text{--}20 \text{ GV}$, depending on the detector location. I adopt the Störmer model, $\mathcal{R}_C(t) = 20 \text{ GV} \rho^{-1}(t) \cos^4 \theta_M(t)$ [40], where $\theta_M(t)$ is the geomagnetic latitude and $\rho(t)$ is the distance between AMS and the geomagnetic dipole center in units of Earth's radii. Their evolution depends on the ISS orbit around the Earth. The function \mathcal{T}_j is computed as $\mathcal{T}_j(E) = \int_{T_0} \alpha(t) \mathcal{H}_j(t, E) dt$, where $\alpha \approx 95\%$ is the detector live-time, and $\mathcal{H}_j(t, E)$ is the geomagnetic transmission function, which is modeled as an \mathcal{R} -dependent smoothed step function, $\mathcal{H} = [1 + (\mathcal{R}/\mathcal{R}_C)^{-12}]^{-1}$. Its particle-dependence arises from the conversion $\mathcal{R} \rightarrow E$, while its time-dependence is contained in $\mathcal{R}_C(t)$. The integral $\mathcal{T}_j(E)$ has been numerically computed for all relevant isotopes by simulating 23,000 ISS orbits with period $T_{\text{ISS}} = 91 \text{ min}$ and inclination $\theta_{\text{ISS}} = 51.7^\circ$. Systematic errors are assigned to be 1.5% for the B/C ratio and 1% on the Be/B ratio, constant in the considered energy range [7]. From the estimated counts, the statistical errors associated with the B/C ratio are given by $1/\sqrt{\Delta N_B} + 1/\sqrt{\Delta N_C}$, and similarly for the Be/B ratio.

III. RESULTS AND DISCUSSIONS

The AMS physics potential — The AMS capabilities in constraining the model parameters are first estimated *without* accounting for nuclear uncertainties. For this purpose, I have performed a scan in the parameter space $D_0 \times L \times v_A$ by running GALPROP 3,420 times over a

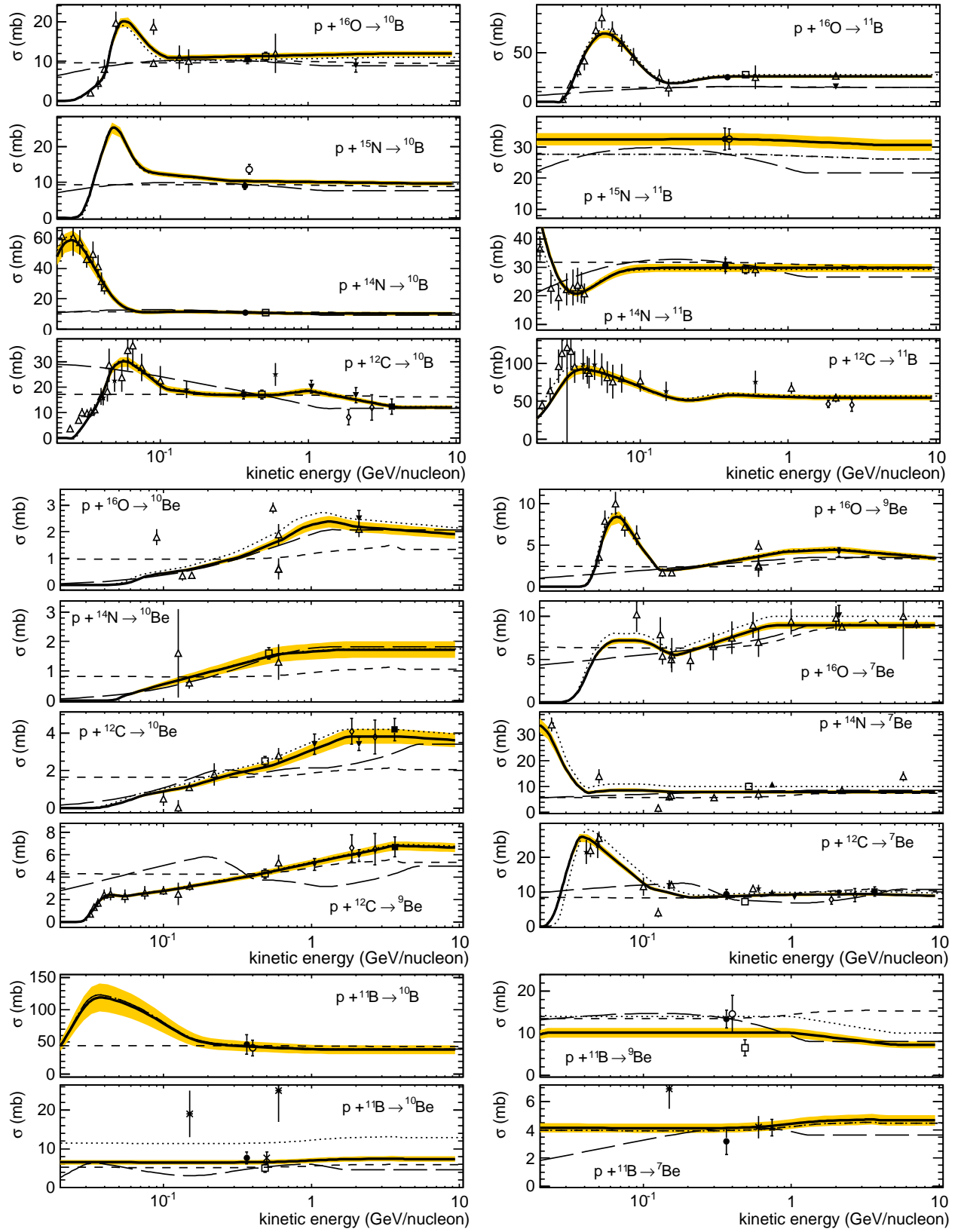


FIG. 2. (Color online) Fragmentation XS's for ^{10}B , ^{11}B , ^7Be , ^9Be , and ^{10}Be production from B-C-N-O collisions off hydrogen. The data are from \triangle : Read & Viola 1984 [21], \bullet : Webber et al. 1998 [22], \square : Webber et al. 1990 [23], \blacktriangledown : Olson et al. 1983 [24], \star : Fontes 1977 [25], \blacksquare : Korejwo 2000 [26], \diamond : Korejwo et al. 2001 [27], \blacktriangle : Radin et al. 1979 [28], \circ : Ramaty et al. 1997 [29], \times : Webber et al. 1998 [30], $*$: Raisbeck1971 & Yiou 1971 [31]. The lines are from the WNEW (short-dashed), YIELDX (long-dashed), GALPROP (dotted), and the XS's determined in this work (thick solid lines) with their uncertainty band.

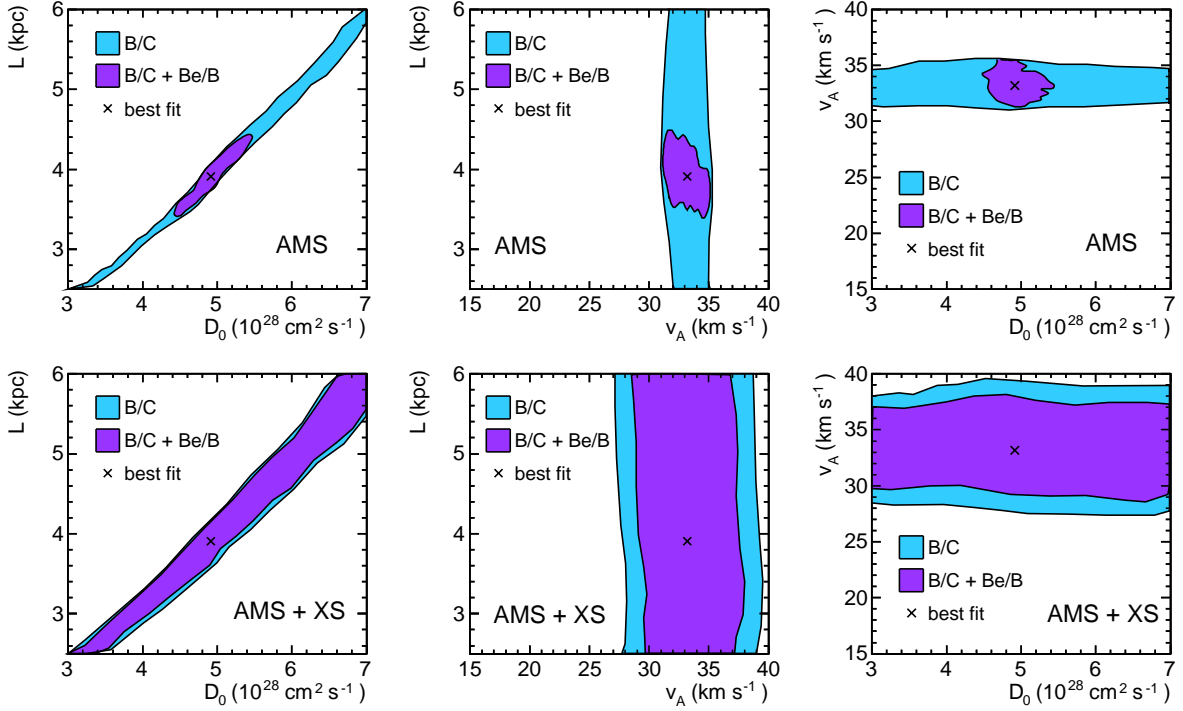


FIG. 3. (Color online) Top: estimation of the AMS capabilities in constraining the parameters D_0 , L , and v_A with the B/C and Be/B ratios. Bottom: same as above after accounting for *nuclear uncertainties* in the Be-B production rates.

$19 \times 15 \times 12$ grid. The resulting spectra are then tri-linearly interpolated to a $4 \times$ finer parameter grid, corresponding to 187,245 models. Hence, the B/C ratio predicted by each model is tested against the artificial AMS data (generated with the reference model of Fig. 1), using the χ^2 method. The same procedure is done for Be/B ratio and for the two combined ratios. The results of are shown in Fig. 3, top panels, where the one-sigma contour regions are plotted as 2D projections of the parameter space. These regions are obtained from the χ^2 surfaces of the B/C ratio and of the B/C+Be/B combination. The best-fit model on each plot (marked as “x”) always recovers the true reference model. The complementarity of the two ratios in breaking the L - D_0 degeneracy is apparent. While the B/C ratio constrains the two parameters into a tight region of the (L, D_0) plane, only the combination B/C+Be/B allows to resolve their single values. The Alfvén speed v_A is well determined by means of B/C data only. Tighter constraints be obtained using data below 2 GeV/n, provided that the solar modulation effect is well modeled. The accuracy of the measured parameters is $\delta D_0 \sim 0.5 \cdot 10^{28} \text{ cm}^2 \text{ s}^{-1}$, $\delta L \sim 0.5 \text{ kpc}$, and $\delta v_A \sim 2 \text{ km/s}$. This level of accuracy, from the estimated AMS capability, would represent quite a significant progress in CR propagation.

Impact of nuclear uncertainties — The models constrained by AMS are shown in Fig. 2 for both ratios (red bands). As clear from the figure, nuclear uncertainties (yellow bands) are dominating. In order to evaluate how these uncertainties affect the parameter reconstruction,

I have repeated the parameter determination procedure after accounting for the XS errors in the χ^2 calculations. The results are shown in the bottom panels of Fig. 3. In comparison with the top panels, one can see that nuclear uncertainties have a dramatic impact on the parameters D_0 and L . As shown in the figure, the D_0/L degeneracy remain essentially unresolved when the nuclear uncertainties are taken into account. In fact, the information needed to break the D_0/L degeneracy is contained in the $^{10}\text{Be} \rightarrow ^{10}\text{B}$ decay which produces only small variations in the Be/B ratio. Along with large uncertainties on the ^{10}Be production, this information is also washed out by uncertainties in the more abundant $^{7,9}\text{Be}$ and ^{11}B components of the Be/B ratio. At this point one may argue that a direct, ideal measurement of ^{10}Be at $\sim 1\text{--}10 \text{ GeV/n}$ would bring tighter constraints. Thus, I have repeated the calculations after considering XS uncertainties for the ^{10}Be production only, *i.e.*, assuming ideal knowledge of the other isotopes and infinite precision measurements. The sole uncertainties in the ^{10}Be production would limit the parameter reconstruction to $\delta D_0 \sim 1.5 \cdot 10^{28} \text{ cm}^2 \text{ s}^{-1}$ and $\delta L \sim 1.5 \text{ kpc}$. This still represents a poor parameter determination in comparisons to the AMS potential. Nonetheless, given the current level of nuclear uncertainties, a direct measurement of ^{10}Be flux (even if affected a few % systematic errors) would probably bring better information than a precise Be/B measurement.

Single-reaction XS bias — It is instructive to study the dependence of the best-fit parameters on single XS reactions. An example is the anti-correlation between

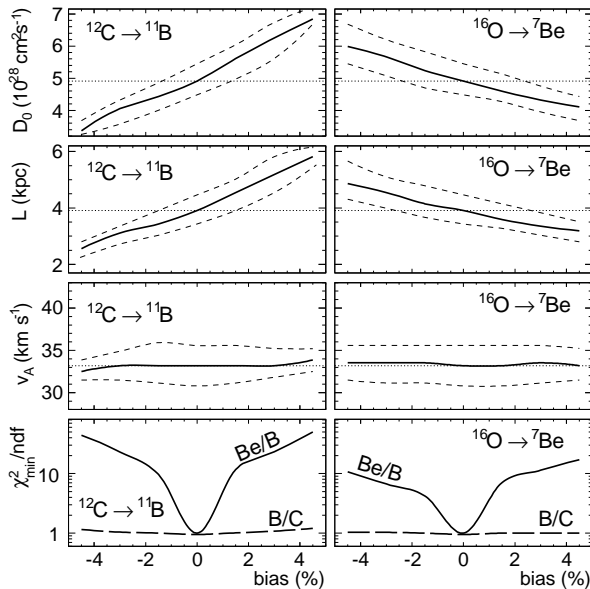


FIG. 4. (Color online) Best-fit parameters D_0 , L , and V_A and the corresponding χ^2_{\min} as a function of the relative bias introduced in the XS normalization for the reactions $^{12}\text{C} \rightarrow ^{11}\text{B}$ and $^{16}\text{O} \rightarrow ^7\text{Be}$.

the reaction $^{11}\text{B} \rightarrow ^{10}\text{Be}$ and the parameter L [41]. Here I consider the reactions $^{12}\text{C} \rightarrow ^{11}\text{B}$ and $^{16}\text{O} \rightarrow ^7\text{Be}$. After the introduction of systematic biases in their XS normalizations, I have generated new reference-model predictions and new AMS mock data. Then, I have repeated the parameters reconstruction procedure using the nominal set of unbiased XS's. The results are shown in Fig. 4. The best-fit parameters are plotted as a function of the bias induced on the XS normalization for the considered reactions. The horizontal dotted lines show the true parameter values. In this case, the best-fit parameters are not correctly reconstructed. While the determination of V_A appears rather stable, the parameter L and D_0 are mis-inferred by large factors after the introduction of a few % deviation in the relevant XSs. This shows, again, that the constraining power of the Be/B ratio is weakened by uncertainties in the ^{11}B or $^{7,9}\text{Be}$ production, rather than by the large errors on the ^{10}Be production. It is also interesting to look at the evolution of the best-fit χ^2_{\min} as function of the bias. This is shown in the bottom panels of the figure. The best χ^2 of the B/C ratio appears insensitive to XS biases. In fact the B/C ratio is approximately given by $\text{B/C} \propto \Gamma_B/(D/L)$,

i.e., any deviation in the B production rate Γ_B can be re-absorbed by a different determination of D_0/L . This is not the case for the Be/B ratio because its high-energy plateau (at $\gtrsim 10$ GeV/n) is almost independent on propagation effects. Hence, discrepancies between Be/B data and model predictions cannot be re-absorbed by the fit in term of different parameter combinations: they can only arise from nuclear physics inputs. An example of this is found in Aguilar et al. [15], where the small discrepancy between the Be/B data and the model predictions was ascribed to the XS's for Be production. The Be/B ratio, like other secondary-to-secondary ratios [42], may be therefore used as a diagnostic tool to detect possible biases in the production XS's.

IV. CONCLUSIONS

My estimates show that the AMS experiment can provide tight constraints on the key parameters D_0 , L , and V_A . Given the level of precision expected by AMS, nuclear uncertainties in secondary production models are found to be a major limitation in the interpretation of secondary CR nuclei. Once nuclear uncertainties are accounted, the D_0/L degeneracy remains poorly resolved. With the current status of nuclear data, the Be/B ratio appears not to bring valuable information for the parameter extraction. Isotopically resolved CR measurements such as the $^{10}\text{Be}/^9\text{Be}$ ratio are preferable, though the ^{10}Be production rate is affected by large uncertainties. On the other hand, precise data on the Be/B ratio at $E \gtrsim 10$ GeV/n may represent a powerful tool to test the nuclear physics inputs of the propagation models, and in particular to detect possible biases in single reactions that may cause a parameter mis-determination. It also worth stressing that this problem has a direct impact in dark matter searches. My study provides a concrete case study for Gondolo's plea to the nuclear physics community [43]. In summary, nuclear uncertainties are a major limiting factor for further progress in CR propagation. The collection of new nuclear data, within a dedicated program of XS measurements and modeling, would enable to fully exploit the potential of the AMS data.

I thank I. Gebauer, F. Donato, L. Derome, D. Maurin, A. Oliva for discussion, I. Moskalenko and the GALPROP team for sharing their code with the community. This work is supported by the ANR LabEx grant ENIGMASS at CNRS/IN2P3.

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